JOURNAL OF GEOPHYSICAL RESEARCH VOL. 69, NO. 4 FEBRUARY 15, 1964

N64-25969
Code None Cat. 04

Aerodynamics of Spherical Balloon Wind Sensors

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Abstract. A preliminary analysis of the response characteristics of spherical balloon wind sensors is presented. It is shown that smooth superpressure spheres do not provide accurate detailed wind profiles and that the response characteristics can be improved by the addition of roughness elements. Experimental data show that surface roughness elements on a spherical balloon stabilize the drag force vector and reduce the lift force. Spurious aerodynamically induced motions are significantly reduced, and the balloon more accurately senses the true wind.

Introduction. Wind sensors of a more or less spherical shape have been employed for many years. Winds are normally measured by tracking a helium- or hydrogen-filled neoprene or rubber balloon which expands as it rises. Positions of the balloon in space are determined by tracking it either with radar or theodolites. Wind profile data are calculated from the balloon positions. Most of the data measured in this way are averaged over an altitude layer of 600 m or more. This averaging process eliminates small-scale motions which would be indicated if the balloon were tracked precisely. Therefore, for making such averaged measurements, it is not necessary that the aerodynamics of the sensor be accurately known. However, if accurate measurements are to be made at close intervals in space so that small-scale motions can be determined, the aerodynamic properties of the wind sensor must be established.

It has been known for many years that vertical gradients in the atmosphere are many times larger than horizontal gradients. For example, wind shears over relatively small distances have been determined to be 50 or more times greater in the vertical than in the horizontal direction. For design and flight testing of vertically rising vehicles, particularly the larger types, it is important that the detailed characteristics of the wind field be specified in the vertical direction [*Vaughan et al.*, 1963]. The usual methods for making wind profile measurements are not adequate for this purpose.

Leviton [1962] proposed that a superpressure Mylar constant volume sphere be used as a wind sensor, and tracked by a precision radar, AN/FPS-16 [*Getler*, 1962], to obtain wind data. In his paper Leviton performed an analysis of the response characteristics of the sphere, assuming a constant drag coefficient, and showed that the sphere's response is adequate to represent small-scale features of the wind field. A similar analysis by *Johnston* [1962] supported this conclusion. Since this method looked promising, the NASA Marshall Space Flight Center initiated tracking of spherical balloons on a limited basis in November 1961 at Cape Canaveral (renamed Cape Kennedy), Florida. Preliminary analyses were made and reported [*Scoggins*, 1962, 1963*a*, 1963*b*] before it was realized that the small-scale features, as indicated by the detailed profiles, did not truly represent atmospheric motions. In early 1963 a NASA program was initiated to evaluate the aerodynamic properties of spheres, and on March 18 the first series of tests were made using spheres of different sizes. Since that time four additional series of tests (some of them in stable air) using spheres, pibals, and standard neoprene sounding balloons have been conducted. Another series of tests was conducted indoors by the NASA Langley Research Center and the U. S. Army Signal Research and Development Laboratory at Lakehurst, New Jersey, on April 23, 1963. Quantitative results of the indoor tests are not yet available. Photographs of these tests confirmed previous results by *Killen* [1960]: spherical balloons do not rise vertically in a calm atmosphere.

The purpose of our tests was to evaluate the influence of surface roughness, weight, ascent rate, and other balloon properties on the response characteristics as a function of Reynolds

number. Preliminary results of the tests conducted at the Marshall Space Flight Center are presented in this paper because of the widespread interest in the subject; however, a more complete and detailed report is being prepared. Further tests are planned which are aimed at specifying the optimum physical characteristics of a sphere for use as a high-resolution or detailed wind profile sensor.

Theoretical considerations. Experimental results of flow around spheres are well established and have been presented in many books on mechanical engineering and fluid dynamics [*Goldstein,* 1938; *Schlichting,* 1960]. A brief outline of the results as related to the present problem is presented here.

Consider a sphere rising through the atmosphere in a horizontal wind. Forces which act on the sphere are buoyancy, gravity, drag, and lift. The forces of buoyancy and gravity are easily evaluated and will not be considered in detail here. Drag and lift forces, however, may be highly erratic, and they will be discussed in terms of their influence on the balloon's motions. It will be assumed in this paper that the winds are horizontal. From aircraft observations this assumption appears reasonable except for regions of high instability or large shears.

The buoyant force is directed upward, producing an ascent rate $\dot{z}$. A drag force, $\mathbf{F}_z$, due to the ascent of the balloon, acts opposite to the buoyant force. Another drag force, $\mathbf{F}_x$, due to flow past the balloon in the horizontal direction, acts in the direction of the horizontal wind. The resultant drag force produced by flow around a sphere is given by

$$\mathbf{F} = \tfrac{1}{2}\rho\,|\mathbf{V}|\,CA\mathbf{V} \qquad (1)$$

where ρ is the density of air, $\mathbf{V}$ is the flow relative to the sphere, C is the drag coefficient, and A is the cross-sectional area of the sphere.

The aerodynamic lift force, which acts primarily in the horizontal direction, is perpendicular to the drag force. Although the lift force is determined by the nature of the flow around the balloon, it cannot readily be evaluated. It may be quite large in some cases and have a significant influence on the balloon's motion. *Schlichting* [1960] reported that Prandtl demonstrated that the nature of the flow around a sphere may be altered merely by placing a wire around the equator. The wire acts as a boundary layer transition trip for the air moving around it, and it reduces the laminar separation of the flow. Surface irregularities on a superpressure balloon might be sufficient to induce transition at different points around the sphere. If this happens the separation area will move upstream or downstream on the surface of the sphere and not necessarily in the same direction at all points. This condition will cause changes in the lift and drag forces, with the result that the balloon might experience accelerations. An instant later the flow separation could change, accelerating the balloon in a different direction. These accelerations result in apparent winds due to the self-induced motions of the sphere itself.

With the exception of C, the parameters in (1) may be evaluated from radar tracking and atmospheric sounding data or are known. *Average* accelerations and lift forces are approximately zero, and the buoyant force is equal in magnitude to the sum of gravity and drag forces. Since the forces due to buoyancy and gravity are known, the drag force can be determined. As defined in (1), flow relative to the sphere can be represented in the following component form

$$\mathbf{V} = \mathbf{i}(u - \dot{x}) + \mathbf{j}(v - \dot{y}) + \mathbf{k}\dot{z}$$

where $\mathbf{i}$, $\mathbf{j}$, and $\mathbf{k}$ are unit vectors in the x, y, and z directions, u and v are the component wind speeds along the x and y axes, and $\dot{x}$, $\dot{y}$, and $\dot{z}$ are the component balloon speeds along the x, y, z axes.

The sum of the first two terms can be approximated for aerodynamically unstable balloons by assuming that differences between a mean wind speed profile and indicated speeds at successive 25-m altitude intervals are relative to the balloon in the horizontal direction. The $\dot{z}$ term is evaluated from radar tracking data. For aerodynamically stable balloons, relative motion in the horizontal direction $[\mathbf{i}(u - \dot{x}) + \mathbf{i}(v - \dot{y})]$, is small compared with the ascent rate $\dot{z}$, and it can be omitted without serious error. With these assumptions and approximations the drag coefficient can be computed.

The Reynolds number, which is the ratio of inertial to frictional forces, is given by

$$Re = \rho\,|\mathbf{V}|\,D/\mu \qquad (2)$$

where ρ and $\mathbf{V}$ are as defined in (1) μ is the

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coefficient of viscosity, and D is the balloon diameter.

It was shown by *Schlichting* [1960] and others that the drag coefficient is a function of the Reynolds number. For a sphere at high Reynolds numbers (supercritical), the drag coefficient is small. As the Reynolds number decreases, the drag coefficient goes through a sharp increase in value (critical Reynolds number) and reaches a rather large value at small Reynolds numbers (subcritical). The nature of the flow separation process is quite different at supercritical and subcritical Reynolds numbers. Characteristics of this flow separation process influence the nature of the drag and lift forces and, therefore, the induced motions. At supercritical Reynolds numbers the separation area has moved downstream and is near the back of the sphere. Surface irregularities on the sphere may alter the nature of the boundary layer and separation characteristics, thus producing variations in the magnitude and direction of the lift and drag forces. At subcritical Reynolds numbers, flow separation takes place farther upstream on the sphere and with a smaller variation in these forces. Therefore, at subcritical Reynolds numbers the spherical balloon is more stable, and it gives a better indication of the true wind conditions.

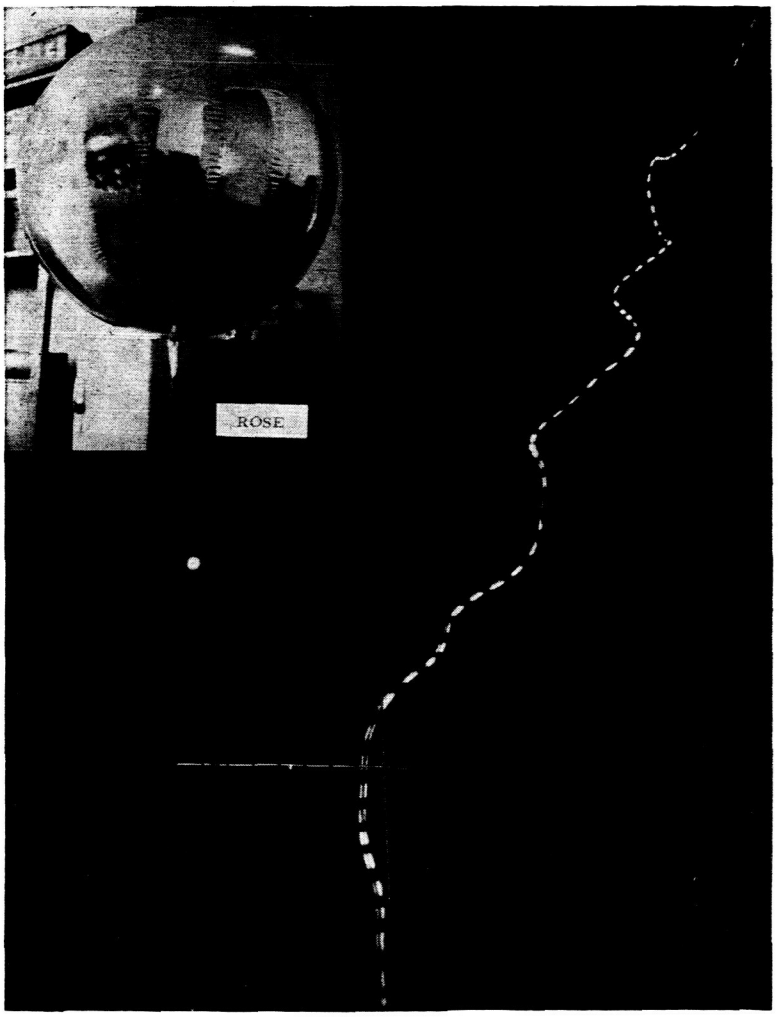

Fig. 1. Time-lapse photograph of Rose balloon released at 11:52 PM, August 2, 1963, during stable atmospheric conditions and light winds.

There are two important factors which must be considered in the design of a spherical wind sensor: the range of Reynolds numbers over which the sphere will be operating and the surface roughness features which affect the wake. As shown by (2), a balloon can be made to operate at low Reynolds numbers by either decreasing its size or decreasing its ascent rate. For small balloons the ascent rate is low and, therefore, the Reynolds number is low. However, with such a balloon, only a limited altitude can be reached. Increasing the surface roughness induces a larger wake behind the sphere and produces larger drag and smaller lift forces at high Reynolds numbers than would be experienced if the roughness elements were not present. The influence of surface roughness on the nature of aerodynamically induced balloon motions will be presented in the following section.

Experimental results. As part of the experimental program being conducted at the Marshall Space Flight Center to evaluate the aerodynamic characteristics of spherical wind sensors and to establish the optimum design, a series of tests was conducted in open air at night on August 2, 1963. The spheres were illuminated by two searchlights and time-lapse photographs were made by two cameras oriented 90° from the launch site at a distance of 375 feet. A chopper was placed in front of the lens to provide an image of the balloon at ½-second intervals. With this chopper arrangement the image was recorded for ¼ of a second and then blanked out for ¼ of a second. A reference cross was placed

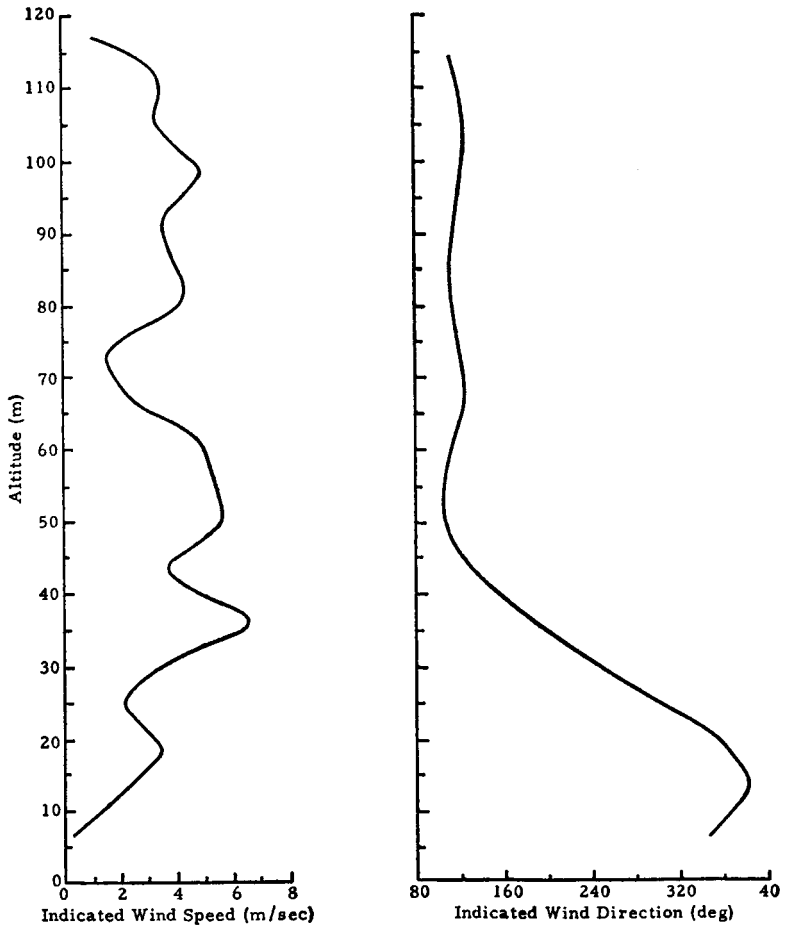

Fig. 2. Rose balloon's horizontal speed and direction profiles (averaged over ½-second intervals).

at 35 feet in front of each camera. This permitted the determination of azimuth and elevation angles at each site, and, through triangulation, the balloon could be tracked in space to obtain wind data. The data reduction procedure is quite simple and is not given here. The time-lapse photograph shown in Figure 1 was made at night during stable conditions and with a surface wind estimated to be less than ½ m/sec. A pilot balloon, tethered at 150 meters, indicated a very slight wind. Figure 1 shows that the balloon followed an irregular path and oscillated several times across the 150-m path that is shown in the photograph. The release time for the Rose balloon was 11:52 PM. Although it is not known what parts of the indicated motions are due purely to winds, it is reasonable to attribute a large part to the aerodynamics of the sphere, since the test was made during stable conditions and very light winds. Profiles are presented in Figure 2 of the Rose balloon's horizontal speed and direction, computed from the time-lapse photograph (Figure 1). Oscillations of the balloon are shown quite clearly in the profiles. The direction profile indicates a reversal in the balloon's direction at a height between 15 and 30 m.

As noted previously, the induced motions due to the aerodynamics of the sphere can be reduced by stabilizing the drag force and reducing the

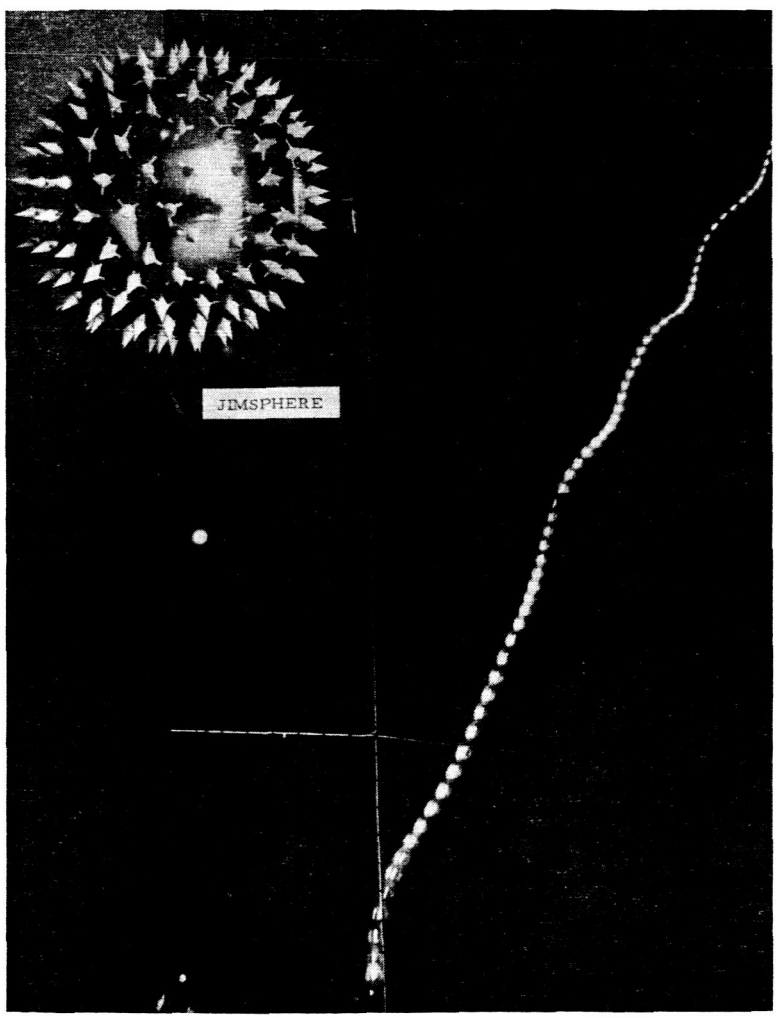

Fig. 3. Time-lapse photograph of Jimsphere balloon released at 11:54 PM, August 2, 1963, during stable atmospheric conditions and light winds.

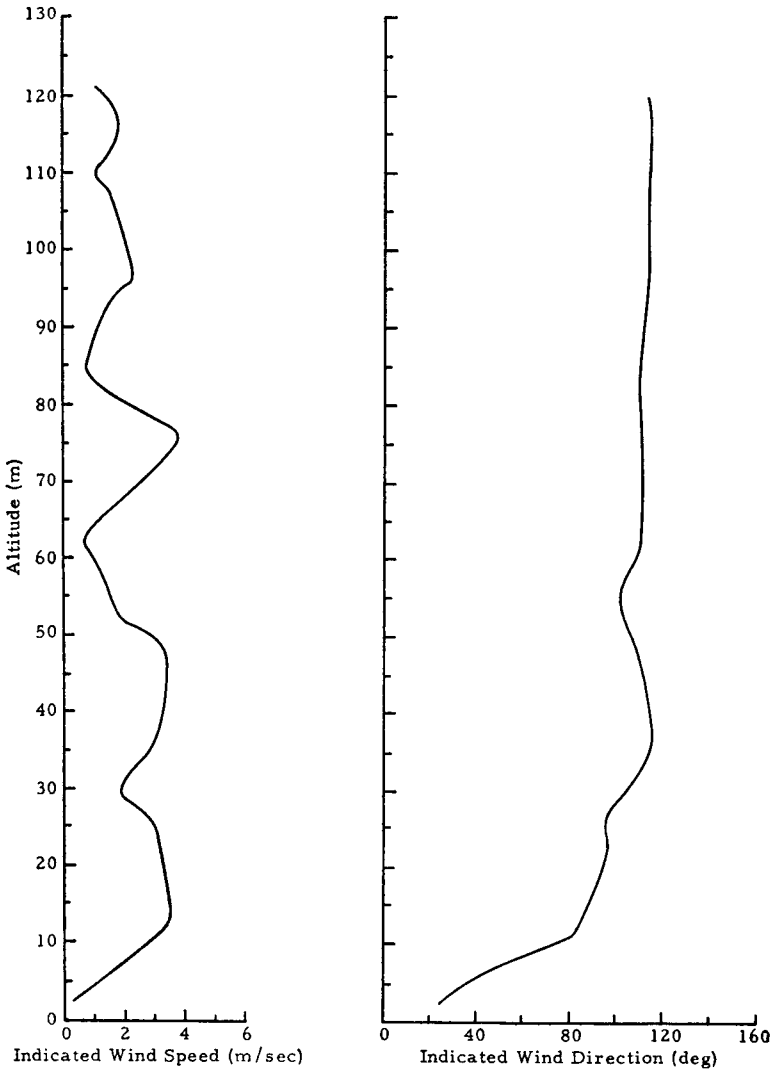

Fig. 4. Jimsphere balloon's horizontal speed and direction profiles (averaged over ½-second intervals).

magnitude of the lift force. This was done by placing surface roughness elements (paper cups) on a Rose balloon. This new configuration is called a Jimsphere. A time-lapse photograph of the ascent of a Jimsphere which was released at 11:45 PM is shown in Figure 3. This balloon configuration experienced smaller oscillations than the Rose through the entire ascent. A comparison of Figures 1 and 3 shows that the Jimsphere was considerably more stable than the Rose. Profiles are presented in Figure 4 of the Jimsphere balloon's horizontal speed and direction, computed from the time-lapse photograph (Figure 3). A comparison of Figures 2 and 4 shows that the oscillations indicated by the Jimsphere have peaks which are approximately half those indicated by the Rose and that a reversal in the balloon's direction did not occur. Although the exact influence of the roughness elements cannot be determined from these measurements, the response of the sphere is changed drastically by the roughness elements. Other measurements made the same night gave similar results.

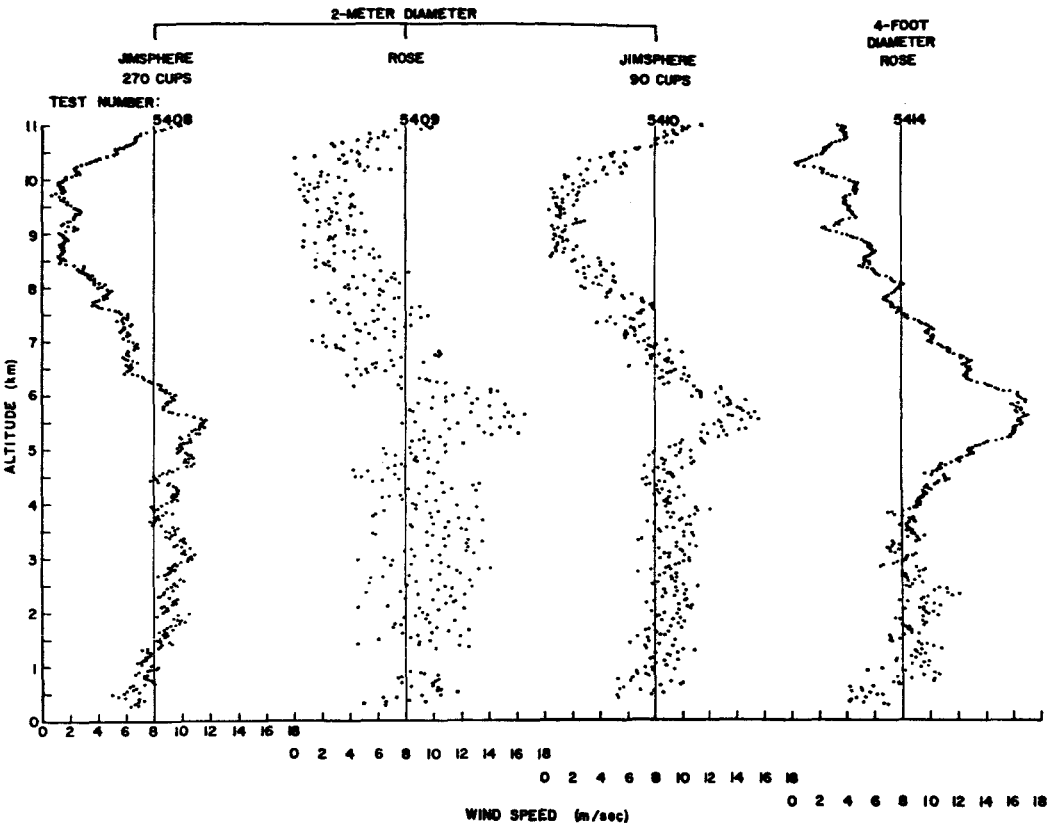

Fig. 5. Scalar wind speed profiles for different balloon configurations.

On August 15, 1963, a series of balloon flights was made at Cape Canaveral. Tracking was done by AN/FPS-16 radar, and data for all flights were reduced by the same method [*Scoggins*, 1963*c*]. Included in these runs were Jimspheres with varying numbers of cups and Rose balloons of two different sizes. The balloons were flown at approximately 1-hour intervals. Four wind speed profiles using different balloon configurations are presented in Figure 5. Test 5408 is a profile obtained from a 2-m-diameter Jimsphere; Test 5409 was obtained from a 2-m-diameter Rose; Test 5410 was obtained from a 2-m-diameter Jimsphere with approximately ⅓ the number of cups as was used in Test 5408; and Test 5414 is a profile obtained from a 1.22-m-diameter Rose. These profiles show dramatically the influence of surface roughness on the response characteristics of a sphere. A comparison of the profiles indicates that as the surface roughness increases the dispersion about a mean profile decreases. This is due apparently to the fact that surface roughness stabilizes the drag force and reduces the influence of lift forces. Preliminary estimates of the drag versus the Reynolds number curve indicate that the 1.22-m-diameter Rose reached the critical Reynolds number at approximately 4-km altitude. Above this altitude the balloon was operating at subcritical Reynolds numbers where the lift forces were apparently smaller and the induced horizontal motions considerably reduced. Eight additional profile measurements made on the same day with Rose and Jimsphere balloons were similar to those reported here.

Conclusions. A smooth spherical balloon wind sensor is not suitable for measuring detailed wind profiles.

As the surface roughness of a sphere increases at supercritical Reynolds numbers, the drag force becomes more stable and the magnitude of the lift force decreases, which, in turn, reduces the magnitude of the aerodynamically induced horizontal motions.

The exact nature of the changes in the aerodynamic properties of a spherical wind sensor due to roughness elements cannot be stated at this time. Future tests are planned which will be aimed at specifying the optimum configuration and at describing the exact influence on the aerodynamic properties due to changes in the physical characteristics of a spherical wind sensor.

Acknowledgments. I wish to express my appreciation to the numerous people at Cape Canaveral and the NASA Marshall Space Flight Center who participated in collecting the experimental data; to Messrs. William W. Vaughan and Michael Susko, Marshall Space Flight Center, and Mr. Henry Jex, Systems Technology, Inc., for their helpful discussions and comments. Special thanks are extended to Professors Hans A Panofsky, Edwin F. Danielsen, John L. Lumley, and Dave F. Hoult, Pennsylvania State University, who reviewed the paper and made notable contributions. Professor Panofsky supervised the work as part of my doctoral program.

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(Manuscript received October 8, 1963; revised November 10, 1963.)